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A.T.I.

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Gt. Brit.
Royal Aircraft
Establishment

Aerodynamics (2)
Stability and Control (1)
Airplanes - Longitudinal stability
(Oct. 72)

80358

AMRO 1821

Note on the principal terms now used in longitudinal stability

Royal Aircraft Establishment, Farnborough, Hants

Gt. Brit. Eng.

Restr. Aug '46 8

The terms static and dynamic stability, stick-free and stick-fixed stability, neutral point, static margin, maneuverability, and derivatives which are the rates of variation of the aerodynamic forces and moments with control settings, velocity components, etc., are explained. Relations between static and maneuver margins and dynamic stability are discussed as to general theory. The instability which occurs when these margins become too small or negative is also discussed.

Air Documents Division, T-2
AMC, Wright Field
Microfilm No.

R 3-111 F 20358

SUITABLE FOR CONTROLLED DISTRIBUTION

TECH REPORT
LOG NO. 435-2-1

Tech. Note No. Aero 1821.

August, 1946.

ATTN No 20358

RESTRICTED Equal
UNITED STATES RESTRICTED

ESTABLISHMENT, FARNBOROUGH

Note on the Principal Terms now used in Longitudinal Stability

Corrigendum

Wright Field

Page 7. Delete asterisks after references 1 and 2.

After reference 2, add "(R & H. 2028)".

Delete footnote.

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Tech. Note No. Aero. 1821.

August, 1946.

ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH

Note on the Principal Terms now used in Longitudinal Stability

1 Introductory

In the consideration of longitudinal stability a distinction is made between static and dynamic stability. Static stability is concerned only with the static moments that develop on an aeroplane in straight flight when it is disturbed slightly from a trimmed state, with the static forces on the aeroplane remaining in equilibrium. The static stability is then a measure of the tendency of these moments to restore the aeroplane to a trimmed state. In the motion that follows the introduction of the disturbance dynamic and inertia forces and moments all contribute to the stability characteristics of the aeroplane, and they are taken into account when dynamic stability is considered. Manoeuvrability, or the response of an aeroplane to the pilot's actions, is very closely connected with dynamic stability and is included in the following discussion.

The rates of variation of the aerodynamic forces and moments with control settings, velocity components, etc. are termed derivatives. These derivatives play a most important part in stability theory. Hitherto many of these derivatives when expressed in a non-dimensional form have been regarded as substantially invariable with speed. Modern aeroplanes, however, are now attaining loadings and speeds at which distortion of the structure and compressibility effects are introducing variations with speed of some of these derivatives, and these variations cannot be neglected. The general theory of longitudinal stability has therefore been extended and the definitions of terms revised to cope with these effects.

2 General Definitions

2.1 Stick Fixed and Free

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Stability is considered in two distinct conditions:

- (a) With the stick (or elevator) set to trim in steady flight and then held fixed throughout the subsequent motion.
- (b) With the trimmer set to trim with zero stick force in steady flight and the stick left free throughout the subsequent motion.

An aeroplane may be stable with stick fixed and unstable with stick free or vice versa. The stick movements which the pilot has to make to control the aeroplane are related to the stick fixed condition, while the forces depend on the stick free condition.

The pilot is most interested in stick free stability, being relatively insensitive to stick movements. The difference between stick fixed and stick free stability depends on the degree of static mass-balance of the elevator and on the design of its aerodynamic balance and is therefore adjustable within certain limits. Stick fixed stability is a property of the design as a whole and herein lies its importance. To

eliminate the effect of distortion of the elevator control circuit, which may vary from one aeroplane to another, it is usual to interpret "stick fixed" as "elevator fixed" at the attachment of the operating lever.

2.2 Static Stability

Static stability can be very easily defined in the simple "basic" case with engine off, when there are no effects, such as those due to slipstream, structural distortion or compressibility, to cause variations in the pitching moment coefficient with speed. In this case it can be said that, when the aeroplane is flying in a straight glide and is displaced through a small angle of pitch, static stability is positive if the static moment tends to restore it to the initial condition, and negative if the initial disturbance tends to increase. As the static stability changes from positive to negative, instability in the form of a divergence develops in the dynamic motion (see para. 2.3). To preserve this relationship between static and dynamic stability in the general case, the definition must include a change in speed as well as incidence when the aeroplane is displaced from the equilibrium condition. The following more precise definition covers all cases.

Suppose an aeroplane is trimmed for straight flight at a given speed, incidence and engine condition and is then held in a current of air at the same engine condition and elevator position but at a slightly higher speed and at the incidence appropriate to straight flight at that higher speed. The aeroplane is then statically stable with stick fixed if the pitching moment tends to restore it to the original incidence. In flight the elevator position must be changed to maintain straight flight at the modified speed, the change being proportional to the restoring or disturbing moment. The aeroplane is therefore stable with stick fixed if the stick is moved forward (elevator down) to trim for straight flight at a slightly higher speed.

The same argument applies with stick free. In this case the aeroplane is statically stable if a push force or upward change in tab angle is required for straight flight at a speed slightly higher than the trimmed speed.

2.3 Dynamic Stability

If the aeroplane is dynamically stable stick fixed, it will, after a small temporary disturbance, return to the initial trimmed state, with the stick held fixed. Similarly, if the stick is left free, and the aeroplane returns to the initial trimmed state, it is said to be dynamically stable stick free. The disturbances in speed and incidence may subside gradually, the amplitude being halved in T seconds, or the speed and incidence may oscillate about the trimmed values. In both cases the damping is measured by $1/T$ where T is the time to halve the amplitude.

For a dynamically unstable aeroplane the speed and incidence may diverge from the trimmed values or may oscillate about them with ever increasing amplitude. The rate of growth is then measured by the time T to double the amplitude (it is then said that the time to halve the amplitude is $-T$).

Immediately after a disturbance the motion is a combination of several modes, but after a short time the heavily damped modes die out and the motion takes the form of the least stable mode. One of the modes will be a divergence when the aeroplane is statically unstable. Thus, a statically unstable aeroplane is also dynamically unstable, but a statically stable aeroplane is not necessarily dynamically stable.

3 Basic Theory of Static Stability

3.1 Assumptions

- (1) The force and moment coefficients C_L , C_D , C_m and C_H are assumed independent of speed and air density. The effects of slipstream, structural distortion and compressibility are thus excluded.
- (2) The air density remains constant during the motion.
- (3) The moment coefficients C_m and C_H are linear functions of incidence and control settings.
- (4) The flight path angle is small, i.e. the lift is equal to the weight of the aeroplane in steady flight.
- (5) The lift on the tail is neglected in comparison with the lift on the wing.

3.2 Neutral Point

The neutral point is the position of the C.G. at which the static stability is neutral. The same elevator angle will, therefore, trim the aeroplane at all speeds when the C.G. coincides with the neutral point with stick fixed. Similarly, at the neutral point with stick free, if the tab angle is set to trim with stick free at one speed, there will be no force on the stick for trim at any other speed. The position of the neutral point is defined as at h_n behind the leading edge of the mean chord with stick fixed and at h'_n with stick free. If the distance of the C.G. from the leading edge of the mean chord is denoted by h , the aeroplane is statically stable with stick fixed when $h < h_n$ and with stick free when $h < h'_n$.

3.3 Static or C.G. Margin

The degree of static stability is measured by the static margin. This is the rate of change of the negative pitching moment coefficient with C_L , where, in accordance with assumption (4) above:

$$C_{m\alpha}^1 \rho v^2 S = W \quad \dots\dots\dots (1)$$

In the basic theory the static margin is also equal to the C.G. margin $h_n - h$ or $h'_n - h$, the distance of the C.G. ahead of the neutral point expressed in terms of the mean chord. Thus, with stick fixed, the static margin is

$$K_n = - \frac{dC_m}{dC_L} \text{ fixed} = h_n - h, \quad \dots\dots\dots (2)$$

where C_m and C_L are measured with the elevator and trimmer fixed. Similarly, with stick free, the static margin is

$$K'_n = - \frac{dC_m}{dC_L} \text{ free} = h'_n - h \quad \dots\dots\dots (3)$$

where C_m and C_L are measured with the trimmer fixed and the stick free.

In flight tests the static margin with stick fixed is determined from the elevator positions required to maintain steady flight at each speed. Thus:

$$K_n = - \frac{\partial C_m}{\partial \eta} \frac{d\bar{\eta}}{dC_L} \dots\dots\dots(4)$$

where $\bar{\eta}$ is the elevator angle required for trim and $\partial C_m / \partial \eta$ is measured with C_L constant. Similarly with stick free

$$K'_n = - \frac{\partial C_m}{\partial \beta} \cdot \frac{d\bar{\beta}}{dC_L} \dots\dots\dots(5)$$

where $\bar{\beta}$ is the tab angle for trim. Alternatively β may be kept constant and the hinge moment coefficient C_H determined from stick force measurements. Then

$$K'_n = - \frac{\partial C_m}{\partial C_H} \frac{dC_H}{dC_L} \dots\dots\dots(6)$$

4. More General Theory of Static Stability

4.1 Assumptions

A more general theory has been developed to include the effects of structural distortion and of compressibility below the shock stall. A detailed description of the theory is impossible here, and reference should be made to R.A.E. Reports^{1,2}. Assumptions (2) and (3) of the basic theory (para. 2.1) are retained. Because of assumption (3) the effects of slipstream or wake are not completely covered, while assumption (4) can be discarded only if the effects of varying air density are neglected.

In the general theory C_L in equation (1) is replaced by $C_R = R / V^2 S$, where R is the resultant of the aerodynamic and tractive forces acting on the aeroplane (lift, drag and propeller thrust).

In general the static margin is not equal to the distance of the C.G. ahead of the neutral point and a clear distinction between static and C.G. margins is essential. The theory stresses the importance of the static margin as the measure of static stability, the position of the neutral point being relatively insignificant.

4.2 Static Margin

With stick fixed

$$K_n = - \frac{dC_m}{dC_R} \text{ fixed} = - \frac{\partial C_m}{\partial \eta} \frac{d\bar{\eta}}{dC_R} \dots\dots\dots(7)$$

where C_m and C_R are measured at the speed V given by the relationship

$$C_R^2 PV^2 S = W \dots\dots\dots(8)$$

and the slope dC_m / dC_R at a given C_R is measured at $C_m = 0$, i.e. with the elevator in the correct position for trim at that C_R . In the estimation of $d\bar{\eta} / dC_R$ from flight tests this condition is automatically satisfied. The slope $\partial C_m / \partial \eta$ is measured with V as well as C_R constant at the appropriate value given by (8).

Similar conditions apply to the measurement of the static margin with stick free.

$$K'_n = - \frac{dC_m}{dC_R} \text{ free} = - \frac{\partial C_m}{\partial \beta} \frac{d\bar{\beta}}{dC_R} = - \frac{\partial C_m}{\partial C_H} \frac{dC_H}{dC_R} \dots\dots\dots(9)$$

also dC_H/dC_R must be measured at the trimmer setting for which $C_H = 0$ at the chosen C_R .

4.3 Neutral Point and C.G. Margin

The neutral point at h_n or h'_n is the C.G. position for which the static margin is zero.

The C.G. margin is given by:

$$\left. \begin{aligned} H_n &= h_n - h \\ H'_n &= h'_n - h \end{aligned} \right\} \dots\dots\dots (10)$$

At any particular speed K_n (or K'_n) is proportional to H_n (or H'_n), but the factor of proportionality varies with speed and may become infinite or negative. Thus it is possible for the neutral point to be ahead of the wing and the C.G. margin to be negative while the static margin is positive. In such cases it is obvious that the static margin and not the C.G. margin defines the degree of static stability.

5 Manoeuvrability

The response to elevator control can be defined in terms of the ratio of the pilot's action in a pull-out from a dive to the centrifugal acceleration built up in the pull-out. This ratio varies with the pilot's technique and the stage reached in the pull-out. To fix a definite criterion it is convenient to assume as an approximation to the behaviour in the pull-out that:

- (a) steady flight in an arc of a circle in the vertical plane at constant speed and centrifugal acceleration ng can be maintained,
- (b) changes in the gravity component during the manoeuvre can be neglected in comparison with the centrifugal acceleration.

The difference, z_g (or F), between the stick position (or force) to maintain the centrifugal acceleration ng and the position (or force) to trim in straight flight at the same speed is proportional to ng , and hence we obtain the criteria:

$$\left. \begin{aligned} (1) \quad Q_1 &= \text{'stick travel per } g' = z_g/n, \\ (2) \quad Q &= \text{'stick force per } g' = F/n. \end{aligned} \right\} \dots\dots\dots (11)$$

The manoeuvre points, stick fixed and free, are the C.G. positions at which Q_1 and $Q = 0$ respectively. They are denoted as being at h_m and h'_m respectively, from the leading edge of the mean chord \bar{c} .

The manoeuvre margins are equal to the distances of the C.G. ahead of the manoeuvre points. They are written as:

$$\left. \begin{aligned} H_m &= h_m - h \text{ with stick fixed} \\ H'_m &= h'_m - h \text{ with stick free} \end{aligned} \right\} \dots\dots\dots (12)$$

The criteria Q_1 and Q are proportional to $H_m C_L$ and $H'_m C_L$ respectively. In the general theory the factor of proportionality is a function of speed.

6 Relationship between Static and Manoeuvre Margins and Dynamic Stability

6.1 Basic Theory

With the simplifying assumptions of the basic theory there is a close relationship between the static and manoeuvre margins, given by:

$$H_m = K_n - \frac{1}{0} \cdot \frac{m_g}{\mu_1} = h_n - h - \frac{\ell}{0} \frac{m_g}{\mu_1}$$

$$H'_m = K'_n - \frac{\ell}{0} \cdot \frac{m'_g}{\mu_1} = h'_n - h - \frac{\ell}{0} \frac{m'_g}{\mu_1}$$

The relative density $\mu_1 = \frac{W}{\rho g S c}$ increases with wing loading and

altitude. The terms $-\frac{\ell}{0} \frac{m_g}{\mu_1}$ and $-\frac{\ell}{0} \frac{m'_g}{\mu_1}$ are due to the angular velocity in the pull-out. On conventional aeroplanes they are respectively equal to $\frac{\bar{V}}{2 \mu_1}$ and $\frac{\bar{V}}{2 \mu_1}$ and represent the damping effect of the tail plane.

The above equations express the fact that the manoeuvre point in the basic case lies aft of the C.G. position for neutral static stability by an amount such that in pitching motion with the C.G. at the manoeuvre point the couple due to the static instability is just balanced by the damping couple. The order of this amount varies from 0.04c for a fighter at high altitude to 0.10c for a large bomber or civil air liner near the ground.

Flight with the C.G. in the region of the manoeuvre point is characterised by a rapid change of normal acceleration following small, and possibly inadvertent, movements of the elevator.

6.2 General Theory

In the general theory changes in the derivatives with speed have a more pronounced effect on the static margin than on the manoeuvre margin, which is related to conditions at constant speed. The result is that, in general, the static margin may be greater or less than the manoeuvre margin by quite large amounts. On the relative values of the two margins depends the relationship between static and dynamic stability, including the behaviour in dives and pull-outs.

6.3 Dynamic Stability

When the static and manoeuvre margins are both large and positive, the motion with stick fixed consists of two oscillatory modes:

- (a) A slowly damped phugoid with a period of the order of 30 seconds.
- (b) A well damped pitching oscillation with a period of from 2 to 8 seconds, generally referred to as the short period oscillation.

With stick free there is an additional heavily damped rapid oscillation of the elevator, and the pitching oscillation may under certain conditions become unstable.

Instability of the following types will occur when the margins become small or negative:

	Type of Instability
(a) $K_n > H_m > 0$	Unstable phugoid oscillation when K_n is large and H_m is small.
(b) $K_n < 0, H_m > 0$	Slow divergence.
(c) $K_n > 0, H_m < 0$	Very unstable oscillation or rapid divergence.
(d) $K_n < 0, H_m < 0$	Rapid divergence.

The behaviour with stick free is similar.

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C.S.(A)	A. & A.E.E.	(3)
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FORM 1 (Rev. 4)

Gt. Brit. Royal
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lishment.

EXTRACTED
DIVISION: Aerodynamics (2)
SECTION: Stability and Control (1) 2-61
CROSS REFERENCE: Airplanes - Longitudinal stability
(054729)

ATL 20358

U.S. AIR FORCE

AERO 1821

EXTRACT

AUTHORITY

ANAL. TITLE: Note on the principal terms now used in longitudinal stability

FORM. TITLE

ORIGINATING AGENCY: Royal Aircraft Establishment, Farnborough, Hants

TRANSLATION:

COUNTRY	LANGUAGE	DOC. CLASS	U. S. CLASS	DATE	PAGES	ILLUS.	FEATURES
Gt. Brit.	Eng.	Restr.	Restr.	Aug '46	8		

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lishment.

DIVISION: Aerodynamics (2)
SECTION: Stability and Control (1)
CROSS REFERENCES: Airplanes - Longitudinal stability
(081729)

ATI- 20358

ORG. AGENCY NUMBER

AERO 1821

REVISION

AUTHOR(S)

AMER. TITLE: Note on the principal terms now used in longitudinal stability

FORG'N. TITLE:

ORIGINATING AGENCY: Royal Aircraft Establishment, Farnborough, Hants

TRANSLATION:

COUNTRY	LANGUAGE	FORG'N CLASS	U. S. CLASS.	DATE	PAGES	ILLUS.	FEATURES
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AD#: ADA800778

Date of Search: 16 Nov 2009

Record Summary: DSIR 23/15825

Title: Principal terms now used in longitudinal stability (RAE TN AERO 1821)
Availability Open Document, Open Description, Normal Closure before FOI Act: 30 years
Former reference (Department): ARC 9988
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